Chapter 2
Optical Fibers

An optical fiber is a cylindrical dielectric waveguide made of low-loss materials such as silica glass. It has a central core in which the light is guided, embedded in an outer cladding of slightly lower refractive index. Figure 1 displays the construction of an optical fiber cable. Light rays incident on the core-cladding boundary at angles greater than the critical angle undergo total internal reflection and are guided through the core without refraction. Rays of greater inclination to the fiber axis lose part of their power into the cladding at each reflection and are not guided. As a result of recent technological advances in fabrication, light can be guided through 1 km of glass fiber with a loss as low as $\approx 0.16\ dB\ (= 3.6\ \%)$. The coating, strength member, and Outer jacket doesn't contribute to light propagation through the fiber but reinforce it to resist factors that may damage the fiber. Optical fibers are replacing copper coaxial cables as the preferred transmission medium for electromagnetic waves, thereby revolutionizing terrestrial communications. Applications range from long-distance telephone and data communications to computer communications in a local area network.

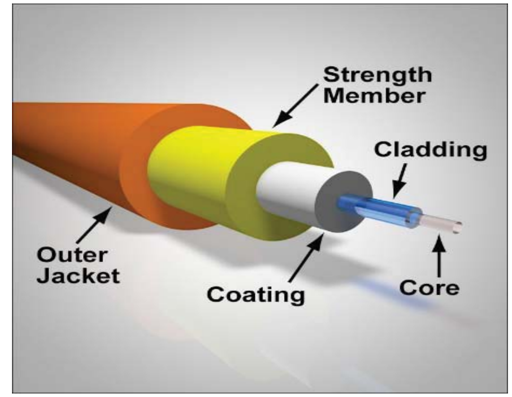


Figure 1: Optical fiber construction

2.1. Total Internal Reflection (TIR)

At the heart of an optical communication system is the optical fiber that acts as the transmission channel carrying the light beam loaded with information. As mentioned earlier, the guidance of the light beam (through the optical fiber) takes place because of the phenomenon of total internal reflection (TIR), which we will now discuss. You learned about critical angles, TIR. You need now to refresh your memory and apply these ideas more directly to the physics of optical fibers. We first define the refractive index (n) of a medium as:

$$n = \frac{c}{v} \tag{1}$$

where $c\ (\approx 3 \times 10^8\ m/s)$ is the speed of light in free space and v represents the velocity of light in that medium. For example, for light waves, $n \approx 1.5$ for glass and $n \approx 1.33$ for water.

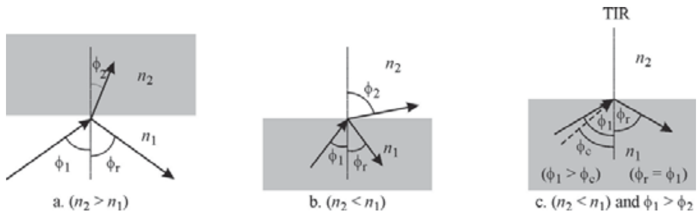


***Figure 2:** (a) A ray of light incident on a denser medium ($n_2 > n_1$). (b) A ray incident on a rarer medium ($n_2 < n_1$). (c) For ($n_2 < n_1$), if the angle of incidence is greater than the critical angle, the incident ray will undergo total internal reflection*

As you know, when a ray of light is incident at the interface of two media (like air and glass), the ray undergoes partial reflection and partial refraction as shown in Figure 2a. The vertical dotted line represents the normal to the surface. The angles ϕ_1, ϕ_2, and ϕ_r represent the angles that the incident ray, refracted ray, and reflected ray make with the normal. According to Snell's law and the law of reflection,

$$n_1 \sin \phi_1 = n_2 \sin \phi_2 \text{ (Snell's law)} \quad (2)$$

$$\phi_1 = \phi_r \text{ (Law of reflection)} \quad (3)$$

Further, the incident ray, reflected ray, and refracted ray lie in the same plane. In Figure 2a, we know from Snell's law that since $n_2 > n_1$, we must have $\phi_2 < \phi_1$ (i.e., the refracted ray will bend toward the normal). On the other hand, if a ray is incident at the interface of a medium where $n_2 < n_1$, the refracted ray will bend away from the normal (see Figure 2b). The angle of incidence, for which the angle of refraction is 90°, is known as the critical angle and is denoted by ϕ_c. Thus, when

$$\phi_1 = \phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \quad (4)$$

the angle of incidence exceeds the critical angle (i.e., when $\phi_1 > \phi_c$), there is no refracted ray and we have total internal reflection TIR. (Figure 2c).

Example 1

For a glass-air interface, $n_1 = 1.5$, $n_2 = 1.0$, and the critical angle is given by $\phi_c = \sin^{-1}(1.0/1.5) \approx 41.8°$

On the other hand, for a glass-water interface, $n_1 = 1.5$, $n_2 = 1.33$, and $\phi_c = \sin^{-1}(1.33/1.5) \approx 62.5°$.

2.2. The Optical Fiber

An optical fiber (Figure 3) consists of a central glass core of radius "a" surrounded by an outer cladding made of glass with a slightly lower refractive index. The corresponding refractive index distribution (in the transverse direction) is given by:

$$n = n_1 \quad \text{for} \quad r < a \quad (5)$$

$$n = n_2 \quad \text{for} \quad r > a \quad (6)$$

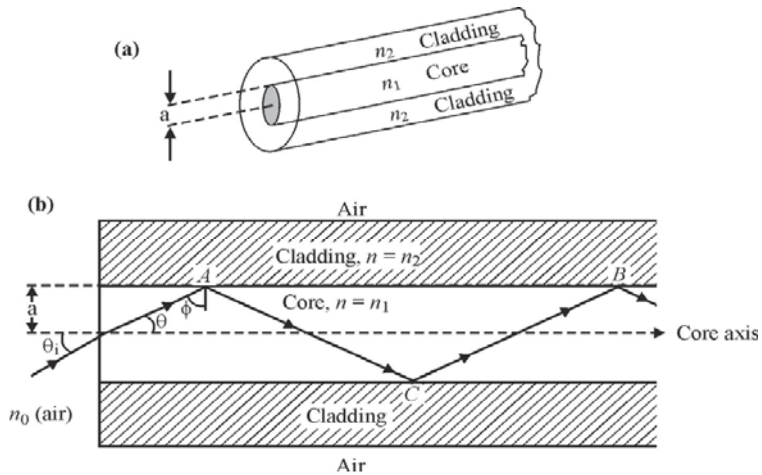


Figure 3: (a) A glass fiber consists of a cylindrical central core surrounded by a cladding material of slightly lower refractive index. (b) Light rays impinging on the core-cladding interface at an angle ϕ greater than the critical angle ϕ_c are trapped inside

Figure 3 shows a light ray incident on the air-core left interface at an angle θ_i. The ray refracts at angle θ in accordance with Snell's law and then strikes the core-cladding interface at angle ϕ. In the drawing shown, the angle ϕ is greater than the critical angle ϕ_c defined in Equation 4-3, thus leading to total internal reflection at *A*. The reflected ray is totally internally reflected again at *C* and *B* and so on, remaining trapped in the fiber as it propagates along the core axis.

The core diameter $d = 2a$ of a typical telecommunication-grade multimode fiber is approximately 62.5 μm with an outer cladding diameter of 125 μm. The cladding index n_2 is approximately 1.45 (pure silica), and the core index n_1, barely larger, around 1.465. The cladding is usually pure silica while the core is usually silica doped with germanium, which

increases the refractive index slightly from n_2 to n_1. The core and cladding are fused together during the manufacturing process and typically not separable. An outside plastic buffer is usually added to protect the fiber from environmental contaminants.

2.3. Numerical aperture

One of the more important parameters associated with fiber optics is the *numerical aperture*.

The numerical aperture of a fiber is a measure of its *light-gathering ability* and is defined by

$$N.A. = Sin\ (\theta_a)_{\max} \tag{7}$$

where $(\theta_a)_{\max}$ is the maximum half-acceptance angle of the fiber, as shown in Figure 4.

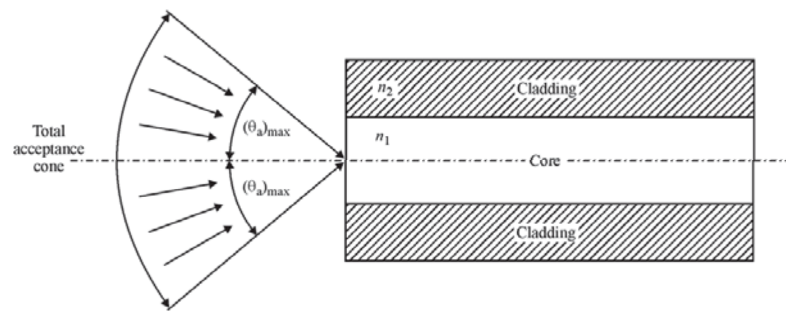


Figure 4: Numerical aperture

The larger the numerical aperture, the greater the light gathering ability of the fiber. Typical values for $N.A.$ are between 0.2 and 0.3 for multimode fiber and 0.1 to 0.2 for single-mode fiber. The numerical aperture is an important quantity because it is used to determine the coupling and

dispersion characteristics of a fiber. For example, a large numerical aperture allows more light to be coupled into the fiber but at the expense of *modal dispersion*, which causes pulse spreading and ultimately bandwidth limitations.

The numerical aperture ($N.A.$) is related to the index of refraction of the core and cladding by the following equation:

$$N.A. = \sqrt{n_1^2 - n_2^2} \tag{8}$$

As can be seen, the larger the difference between the core and cladding index, the larger the numerical aperture and hence more modal dispersion.

The N.A. may also be expressed in terms of the *relative refractive index difference* termed Δ, where

$$\Delta \equiv \frac{n_1^2 - n_2^2}{2n_1^2} \tag{9}$$

so that, with Equation (9), we get Equation (10)

$$\Delta = \frac{1}{2}\left(\frac{N.A.}{n_1}\right)^2 \tag{10}$$

Combining Equations (8) and (10), we obtain a useful relation in (11).

$$N.A. = sin(\theta_a)_{max} = n_1\sqrt{2\Delta} \tag{11}$$

In short, a large $N.A.$ represents a large difference in refractive index, leading to a large acceptance angle and hence a large numerical aperture.

However, this can lead to serious bandwidth limitations. Typical values for Δ range from 0.01 to 0.03 or 1 to 3 %

Example 2

For a typical step-index (multimode) fiber with core index $n_1 \approx 1.45$ and $\Delta \approx 0.01$, we get

$$sin(\theta_a)_{\max} = n_1\sqrt{2\Delta} = 1.45\sqrt{2 \times (0.01)} = 0.205$$

so that $(\theta a)max \approx 12^o$. Thus, all light entering the fiber must be within a cone of half-angle 12^o. The full acceptance angle is $2 \times 12^o = 24^o$.

2.4. Transmission Windows (Bands)

Optical fiber communication systems transmit information at wavelengths that are in the near infrared portion of the spectrum, just above the visible, and thus undetectable to the unaided eye. Typical optical transmission wavelengths are 850 nm, 1310 nm, and 1550 nm. Both lasers and LEDs are used to transmit light through optical fiber. Lasers are usually used primarily for 1310 and $1550 - nm$ single-mode applications. LEDs are used for 850 nm multimode applications.

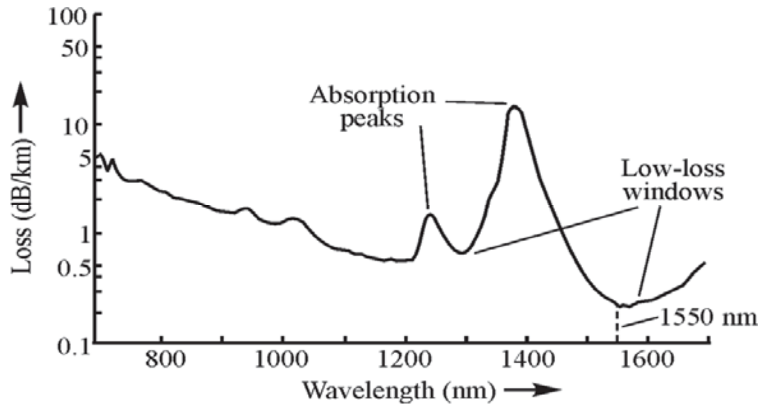


Figure 5: Typical wavelength dependence of attenuation for a silica fiber. Notice that the lowest attenuation occurs at 1550 nm [adapted from Miya, Hasaka, and Miyashita].

Figure 5 shows the spectral dependence of fiber attenuation (i.e., *dB loss per unit length*) as a function of wavelength of a typical silica optical fiber. The losses are caused by various mechanisms such as Rayleigh scattering, absorption due to metallic impurities and water in the fiber, and intrinsic absorption by the silica molecule itself. The Rayleigh scattering loss varies as $1/\lambda_0^4$, i.e., longer wavelengths scatter less than shorter wavelengths. (Here λ_0 represents the free space wavelength.) As we can see in Figure 5, Rayleigh scatter causes the dB loss/km to decrease gradually as the wavelength increases from 800 nm to 1550 nm. The two absorption peaks around 1240 nm and 1380 nm are primarily due to traces of OH ions and metallic ions in the fiber. For example, even 1 part per million (ppm) of iron can cause a loss of about 0.68 dB/km at 1100 nm. Similarly, a concentration of 1 ppm of OH ion can cause a loss of 4 dB/km at 1380 nm. This shows the level of purity that is required to achieve low-loss optical fibers. If these impurities are removed, the two absorption peaks

will disappear. For $\lambda_0 > 1600\ nm$, the increase in the dB/km loss is due to the absorption of infrared light by silica molecules. This is an intrinsic property of silica, so no amount of purification can remove this infrared absorption tail.

As you see, there are two windows at which the dB/km loss attains its minimum value. The first window is around 1300 nm (with a typical loss coefficient of less than 1 dB/km) where, fortunately (as we will see later), the material dispersion is negligible. However, the loss coefficient is at its absolute minimum value of about 0.2 dB/km around 1550 nm. The latter window has become extremely important in view of the availability of erbium-doped fiber amplifiers.

Overall, there are ranges of wavelengths at which the fiber operates best. Each range is known as an operating window. Each window is centered on the typical operational wavelength, as shown in Table 1.

Table 1: Fiber Optic Transmission Windows

Window	Operating Wavelength
800 – 900 nm	850 nm
1250 – 1350 nm	1310 nm
1500 – 1600 nm	1550 nm

These wavelengths were chosen because they best match the transmission properties of available light sources with the transmission qualities of optical fiber.

2.5. Types of fiber

The optical fibers can be classified according to the profile of the refractive index (or the distribution of values of the refractive index across the cross section of the fiber) and size of the core into

- Multimode Step-Index
- Multimode Graded-Index
- Single-Mode (Step-Index)

Figure 6 shows the three different profiles of refractive index for the above fiber types.

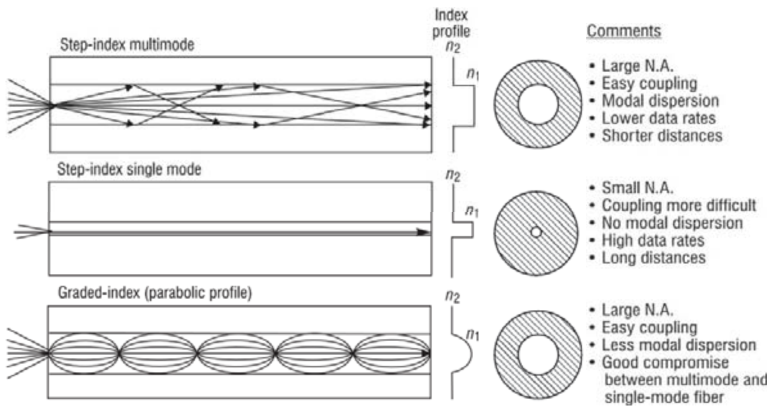


Figure 6: Refractive Index Profiles

The difference between them is in the way light travels along the fiber. The top section of the figure shows the operation of "multimode" fiber. There are two different parts to the fiber. In the figure, there is a core of 50 microns (μm) in diameter and a cladding of 125 μm in diameter. (Fiber size is normally quoted as the core diameter followed by the cladding diameter.

Thus, the fiber in the figure is identified as 50/125.) The cladding surrounds the core. The cladding glass has a different (lower) refractive index than that of the core, and the boundary forms a mirror.

This is the effect you see when looking upward from underwater. Except for the part immediately above, the junction of the water and the air appears silver like a mirror.

Light is transmitted (with very low loss) down the fiber by reflection from the mirror boundary between the core and the cladding. This phenomenon is called "total internal reflection". Perhaps the most important characteristic is that the fiber will bend around corners to a radius of only a few centimeters without any loss of the light.

Multimode Step-Index Fiber

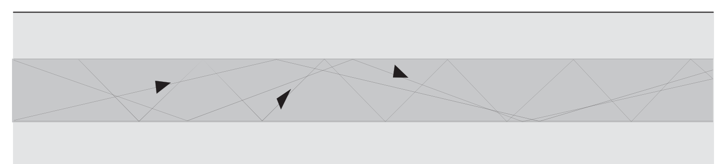


Figure 7: Multimode Step-Index Fiber

The expectation of many people is that if you shine a light down a fiber, then the light will enter the fiber at an infinitely large number of angles and propagate by internal reflection over an infinite number of possible paths. This is not true. What happens is that there is only a finite number of possible paths for the light to take. These paths are called "modes" and identify the general characteristic of the light transmission system being used. Fiber that has a core diameter large enough for the light used to find

multiple paths is called "multimode" fiber. For a fiber with a core diameter of 62.5 microns using light of wavelength 1300 nm, the number of modes is around 400 depending on the difference in refractive index between the core and the cladding.

The problem with multimode operation is that some of the paths taken by particular modes are longer than other paths. This means that light will arrive at different times according to the path taken. Therefore, the pulse tends to disperse (spread out) as it travels through the fiber. This effect is one cause of "intersymbol interference". This restricts the distance that a pulse can be usefully sent over multimode fiber.

Multimode Graded Index Fiber

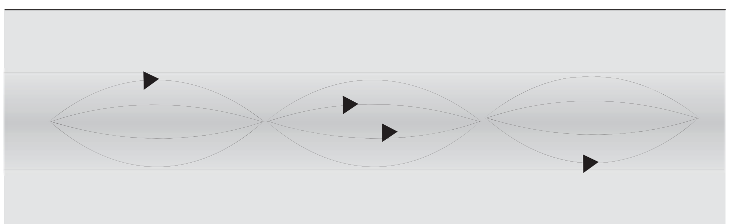


Figure 8: Multimode Graded index Fiber

One way around the problem of (modal) dispersion in multimode fiber is to do something to the glass such that the refractive index of the core changes gradually from the center to the edge. Light travelling down the center of the fiber experiences a higher refractive index than light that travels further out towards the cladding. Thus, light on the physically shorter paths (modes) travels more slowly than light on physically longer paths. The light follows a curved trajectory within the fiber as illustrated in the figure. The aim of

this is to keep the speed of propagation of light on each path the same with respect to the axis of the fiber. Thus, a pulse of light composed of many modes stays together as it travels through the fiber. This allows transmission for longer distances than does regular multimode transmission. This type of fiber is called "Graded Index" fiber. Within a GI fiber light typically travels in around 400 modes (at a wavelength of 1300 nm) or 800 modes (in the 800 nm band).

Note that only the refractive index of the core is graded. There is still a cladding of lower refractive index than the outer part of the core.

Single-Mode Fiber

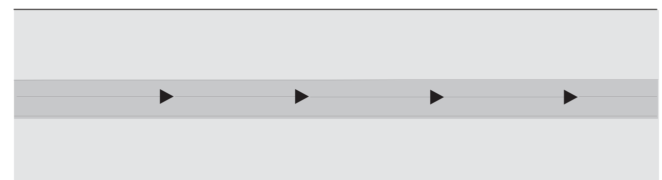


Figure 9: Single-Mode Fiber. Note that this figure is not to scale. The core diameter is typically between 8 and 9 microns while the diameter of the cladding is 125 microns.

If the fiber core is very narrow compared to the wavelength of the light in use then the light cannot travel in different modes and thus the fiber is called "single-mode" or "monomode". There is no longer any reflection from the core-cladding boundary but rather the electromagnetic wave is tightly held to travel down the axis of the fiber. It seems obvious that the longer the wavelength of light in use, the larger the diameter of fiber we can use and still have light travel in a single-mode. The core diameter used in a typical single-mode fiber is nine microns.

It is not quite as simple as this in practice. A significant proportion (up to 20%) of the light in a single-mode fiber actually travels in the cladding. For this reason the “apparent diameter” of the core (the region in which most of the light travels) is somewhat wider than the core itself. The region in which light travels in a single-mode fiber is often called the “mode field” and the mode field diameter is quoted instead of the core diameter. The mode field varies in diameter depending on the relative refractive indices of core and cladding,

Core diameter is a compromise. We can't make the core too narrow because of losses at bends in the fiber. As the core diameter decreases compared to the wavelength (the core gets narrower or the wavelength gets longer), the minimum radius that we can bend the fiber without loss increases. If a bend is too sharp, the light just comes out of the core into the outer parts of the cladding and is lost.

You can make fiber single-mode by:

- Making the core thin enough
- Making the refractive index difference between core and cladding small enough
- Using a longer wavelength

Single-mode fiber usually has significantly lower attenuation than multimode (about half). This has nothing to do with fiber geometry or manufacture. Single-mode fibers have a significantly smaller difference in refractive index between core and cladding. This means that less dopant is needed to modify the refractive index, as dopant is a major source of attenuation.